METHODS FOR DETERMINING ROOF FALL RISK IN UNDERGROUND MINES

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Abstract

Reducing the number of roof fall injuries is a goal of the NIOSH mine safety research program. Central to this effort is the development of assessment techniques that will help to identify the nature of the risks associated with working under potentially hazardous roof conditions. This paper discusses a method to determine the roof fall risk using a qualitative risk analysis technique. The ability to determine roof fall risk has been a long-standing goal of safety professionals and can provide the kind of information, needed by on-site personnel responsible for worker safety, to mitigate roof fall injuries.

Background

A realistic goal for underground mines, trying to reduce incidence of miner injuries associated with roof falls, is to assess the conditions that pose a roof fall risk. If mine operators properly assess roof fall risks, they can better reduce roof fall hazards with appropriate engineering and administrative controls. Any methodology that helps attain this goal can be thought of as a roof fall risk assessment method. An effective roof fall risk assessment method includes the ability to observe variable roof conditions and assess how much these conditions represent the potential for a roof fall capable of injuring miners. This methodology should rank the risk associated with varying conditions, be reasonably reproducible, and indicate clearly roof fall risk to all personnel at a mine responsible for design, approval, or installation of controls that either stabilize the roof or lessen the exposure to roof falls. This paper will focus on the risk assessment issues, leaving the other half of the roof fall risk management process, where controls are designed and used to reduce risk, to another discussion.

One of the most important safety issues at any mining site is the need to identify the location and nature of roof fall hazards. The mining law requires that roof falls be reported to enforcement agencies, but does not specify how this information is displayed or communicated to mine workers. Practices vary widely throughout the mining industry. The Code of Federal Regulations defines a reportable roof fall as "an unplanned roof fall at or above the anchorage horizon in active workings where roof bolts are in use; or, an unplanned roof or rib fall in inactive workings that impairs ventilation or impedes passage" (Anon, 2005). In general, regulatory roof fall reporting requirements consist of time, date and location information. However, for non-injury roof falls, the mine operator is required to submit additional information on the type of mining method, the equipment involved, and a narrative to fully describe the conditions contributing to the roof fall and to quantify the damage.

Why is a Roof Fall Risk Assessment Method Important for Improving Miner Safety?

The potential for roof falls in underground mines is a significant danger for mine workers. During the 10-year period from 1996 until 2005, 7,738 miners were injured from roof falls in underground coal, metal, non-metal and stone mines (MSHA, 2005). Coal mines had the highest rate, 1.75 roof fall injuries per 200,000 hours worked underground (Table 1. see Appendix A). While this rate dropped over this period, 2005 still recorded 581 roof fall injuries, with many classified as severe. Fatal injury trends from 1996 to 2005 were equally troubling, with 100 roof fall fatalities. While coal mining had the highest number with 82, metal mining had the highest rate with 0.03 fatalities per 100,000 miners (Table 1). These statistics attest to the seriousness of this safety issue, although roof fall injuries decreased from 1.71 in 1996 to 1.19 in 2005 per 200,000 hours worked (Table 1). Clearly, progress in miner safety has been made, but further improvement is possible. Through the first 10 months of 2006, nine fatal roof fall injuries occurred (Table 2). It is imperative that new safety techniques and methodologies continue to be developed, so this downward trend in roof fall injures can be maintained.

Table 2. Fatal roof fall injuries in underground coal mines during the first 10-months of 2006.

Date	Mine	Company	State
1/10/06	#1	Maverick	KY
1/29/06	Aberdeen	Andalex	UT
2/1/06	#18 Tunnel	Long Branch	WV
2/16/06	HZ4-1	Perry County	KY
3/29/06	#4	Jim Walter	AL
4/20/06	#1	Tri Star	KY
	#2	D & R	KY
10/11/06	#7	Jim Walter	AL
10/20/06	Whitetail Kittanning	Alpha Natural Resources	WV

What Characteristics Are Needed for an Effective Roof Fall Risk Assessment Method?

The process to assess risk and implement controls to manage these risks can be thought of as a series of steps (Figure 1). The first step is to recognize and rank defective roof conditions within active portions of the mine. By doing this, hazards are identified and some attempt can be made to rank these hazards from low to high. The next step uses a wide variety of risk analysis techniques to determine roof fall probability associated with specific conditions. Miner exposure, a key element in assessing risk, is next determined by estimating the amount of time miners are expected to occupy the different locations within the active underground workings. Combining the probability of roof falls with the estimations of miner exposure yields a suite of roof fall risk levels that is tied to changing roof conditions. Because risk can be ranked across the mine, risk management methods can be used to determine how to mitigate the risk.

What is the State-of-Practice for Roof Fall Risk Assessment?

Most safety decisions in the US mining industry are guided by company policy and the requirements of state and federal regulations. These decisions have been successful in reducing roof fall injuries (Table 1). For this study, our underlying assumption is that incorporating risk assessment and risk management methods to the existing decision-making process will help to further reduce miner injury rates. Risk assessment and risk management methods are widely accepted techniques producing a wide range of standards and guidelines defining there use from organizations like the International Organization for Standardization (ISO) and the American National Standards Institute (ANSI).

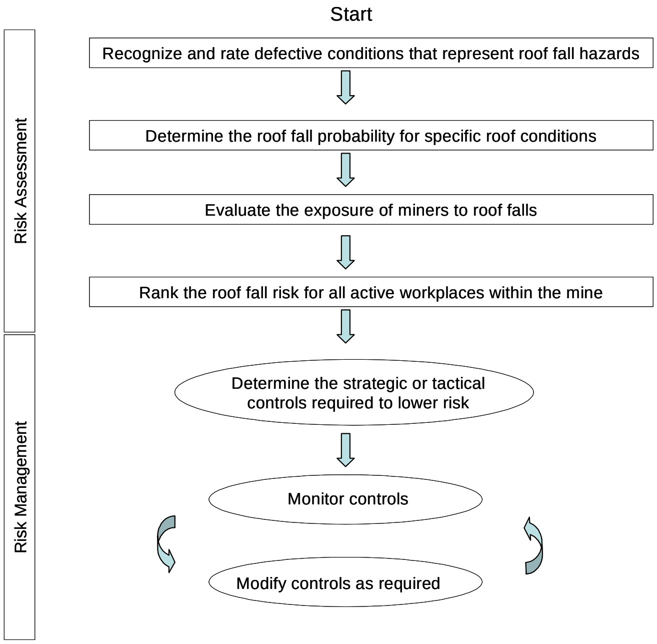

Figure 1. Flow diagram depicting the generalized structure of a roof fall risk assessment activities and its relation to risk management activities.

When applied to a particular industry, the issues unique to that industry require special approaches. For example, the environmental and health sciences have long used risk assessment and risk management methods to identify the highest environmental and occupational health and safety risks and to develop controls specific to their operational and regulatory environments (NRC, 1983, NRC, 1994, and NRC, 2006). Risk assessment and risk management methods for the mining industry are more prevalent in countries with safety standards that emphasize duty-of-care rather than prescriptive health and safety regulations. Australia has embraced this approach more than any other major mining country, but Canada, the United Kingdom, and South Africa also have a strong reliance on risk assessment and risk management methods.

In the early 1990s, the United Kingdom (UK) developed a code of practice (now referred to as Industry Guidance) for rockbolt use as roadway supports that included geotechnical assessment, initial design, design verification, and routine monitoring (Arthur, et al., 1998). Cartwright and Bowler (1999) provided a UK example of a procedure to assess the risk associated with potential failure or overloading of rockbolt support systems. In the mid 1990s, South African mines developed codes of practice to combat rock fall and rock burst accidents, as required by its 1996 Mine Health and Safety Act (Gudmanz, 1998). Swart and Joughin (1998) discussed the importance of rock engineering in developing this code of practice. Van Wijk, et al. (2002) developed a risk assessment method for use in South African coal mines. This risk assessment method aims to optimize resources and focuses attention on the areas where it is most required. Lind (2005) demonstrated an integrated risk management method that required a basic assessment of physical parameters such as coal seam characteristics, depth below surface, and mining conditions.

In the mid 1990s, Australia's coal mining industry became heavily involved in risk management methods typically consisting of structured, team-based exercises to review potential problems carefully with new or existing mining methods, new equipment, or other operational problems (Joy, 2001). Joy estimates that at least 80% of all Australian coal mines have performed some form of structured, team based risk assessment/risk management. Tools used in these exercises include HAZOP (Hazard and Operability Analyses), FMECA (Failure Modes, Effects and Criticality Analysis), and WRAC (Workplace Risk Assessment and Control). In addition, the Minerals Council of Australia (MCA) helped produce a national guideline for the management of roof fall risks in underground metalliferous mines (MOSHAB, 1997). Potvin and Nedin (2003) published a 'Reference Manual' in support of the MCA guidelines meant as a collection of techniques and examples of good roof control practices. Lastly, the Minerals Industry Safety and Health Centre (MISHC) website is an excellent source for information on Australia's diverse risk assessment/risk management approaches (www.mishc.up.edu.au).

Several Roof Fall Hazard Assessment Techniques Have Been Suggested

Risk assessment methods provide a systematic approach to identifying and characterizing risks, especially those associated with low-probability, high-consequence events like roof falls. The first step in utilizing a roof fall risk assessment method requires identification of the potential roof fall hazards. Because local geologic, stress, and mining conditions interact to create varying roof conditions, commodity-specific or activity based hazard assessment techniques and associated risk analysis techniques are needed to locate potential risk within workplaces throughout the mine. Many hazard assessment techniques generally can be classified into three groups: 1) hazard maps, 2) rock mass classification systems, and 3) monitoring data.

Hazard Maps

Hazard maps typically focus on specific geologic or rock properties and are generally represented in some fashion on a mine map. The many kinds of hazard maps that have been developed provide a powerful technique to identify roof fall hazards (Moebs, 1977; Lagather, 1977; Hylbert, 1978; Ellison and Scovazzo, 1981; and Iannacchione, et al., 1981; Chase, et al., 2006). However, most hazard maps don't determine the probability of occurrence for roof falls. This is a fundamental requirement for any roof fall risk assessment method. Some of the issues associated with using hazard identification and assessment methods within risk assessment/risk management approach for major Australian industries are discussed in DIPNR (2004) and DUTP (2003).

Rock Mass Classification Systems

Rock mass classification systems (RMCS) typically focus on determining the relative structural strength of local geologic sequences. Bieniawski (1989) states that the role of rock mass classification is to "consider the engineering properties of both intact rock and the rock mass." Early rock mass classification consisted of Terzaghi's rock load classification (1946) and Deere and Deere's (1988) Rock Quality Designation (RQD). Bieniawski (1973) developed the Rock Mass Rating (RMR) that incorporated six parameters to classify a rock mass (Table 3). Around the same time Barton et al. (1974) developed the Q-system that also incorporated six parameters to classify a rock mass. In the 1990s, NIOSH's Coal Mine Roof Rating System (CMRR) was developed specifically for U.S. coal mining conditions (Molinda and Mark, 1994). It incorporated 5 parameters to classify a rock mass where strong beds can have a significant influence (Table 3).

The RQD, RMR, Q-system, and CMRR, as well as other rock mass classification systems not mentioned here, have become very popular and are used in many geotechnical projects around the world for engineering design purposes. In general, these systems have been used at site-specific locations within a mining operation to characterize roof conditions. However, each of these systems requires data that are somewhat difficult to acquire on the large scale needed to measure the conditions at all accessible sites within a mining operation. Bieniawski (1989) provides one example from a thesis by Ferguson in 1977 (University of Rhodesia). The rock mass quality was contoured over a portion of a mine that used the RMR, depicting different engineering conditions for mineral extraction. In this example, the RMR effectively became a hazard assessment technique. However, rock mass classification systems were not specifically designed to interface with a roof fall risk assessment method and like the hazard maps do not adequately address issues related to the probability and consequence of roof falls events.

Table 3 Important parameters of three popular Rock Mass Classification Systems.

Systems	Important parameters
Rock Mass Rating	Unconfined Compressive Strength
	Rock Quality Designation
	Spacing of discontinuities
	Condition of discontinuities
	Groundwater conditions
	Orientation of discontinuities
Q-system	Rock Quality Designation
	Number of joint sets
	Roughness of alteration or filling along the weakest joint
	Degree of alteration or filling along the weakest joint
	Water inflow
	Stress condition
Coal Mine Roof Rating	Unit rating for distinct rock intervals (cohesion, roughness)
	Intensity of discontinuities (spacing, persistence)
	Number of discontinuity sets
	Unconfined Compressive Strength or Point Load Index
	Moisture sensitivity

Monitoring Data

Monitoring data has been used to establish trends that anticipate or forecast roof falls and represents the third category of hazard assessment techniques. Maleki and McVey (1988) presented a comprehensive analysis of instruments used to monitor roof deformations associated with unstable roof conditions. Cartwright and Bowler (1999) discussed a roof fall risk assessment technique to address roadway instability events at the Thoresby Colliery in the UK. In this case, telltales were deployed in significant concentrations so that reliable action levels were developed from roof deformation data. Typically, action levels used in the UK coal mines are based on the measurement of 25 mm of roof deformation, but can vary based on local mining conditions. At Thoresby Colliery, the hazard assessment technique consisted of measuring roof deformation over 20 m of entry length and when certain levels of movement occurred, a hazard was perceived, and controls were implemented. Stewart and Spottiswoode (1996) developed a means to determine seismic risk of small-scale earthquake-like events associated with deep-level mining in South Africa. The seismic risk is calculated from a number of different categories derived from the microseismic monitoring data collected at the mining operation. In another study at the Moonee Colliery in Australia, the detection of microseismic activity was used to routinely forecast major gob caving events associated with longwall mining (Iannacchione, et al., 2005).

Of the three hazard assessment techniques discussed, only monitoring data have been used, on a limited basis, to assess risk. Unfortunately, the need for complete coverage over even a small portion of an active mining property, translates into large numbers of sensors. This produces considerable operational challenges.

The Roof Fall Risk Index

Because of limitations associated with current hazard assessment techniques, NIOSH developed the Roof Fall Risk Index (RFRI) to be part of an overall roof fall risk assessment method. The RFRI focuses on the character and intensity of defects associated with specific roof conditions and attempts to incorporate some of the characteristics discussed in the other hazard assessment techniques (Iannacchione, et al., 2006; Iannacchione, et al., 2007). The defects measured within the RFRI can be caused by a wide range of local geologic, mining and stress factors and are equated directly to changing roof conditions causing roof fall hazards. A significant range of defects found at underground stone mines are classified into 10 categories (known as *defect categories*), each of which is assigned an assessment values, ranging from 1 to 5, the numerical value increasing with the severity of the defects. To calculate the RFRI, determine the assessment value for each defect category, multiply by an assigned weight (either 1 or 2), add all category values together, and multiply by 1.11. Ideally, values approaching 0 represent safer roof conditions, while an RFRI approaching 100 represents a serious roof fall hazard.

The RFRI is a hazard assessment technique that can be used as both a training and communication tool. This technique requires that roof fall hazards be mapped and the spatial distribution within the underground workplace determined. The RFRI strives to assess roof conditions over large, continuous areas, with fewer time-consuming measurements than are used in many existing rock mass classification systems. This produces a more comprehensive assessment of changing roof conditions than was previously possible.

Moving from Hazard Assessment to Risk Assessment

Ideally, a hazard assessment technique should be capable of ranking the various hazards by the level of risk they present and communicating these risks to the persons or groups in need of this information. These actions would result in safety controls that could improve roof stability or lower miner exposure to hazardous conditions, both of which are critical to reducing roof fall injuries. Typically risk assessment methods determine the risk of an unwanted event by inferring or calculating the event probability of occurrence versus the consequence of the event (Equation 1):

$$\text{Risk} = \text{Probability of Occurrence} \times \text{Consequence} \quad (1)$$

Of the many different risk assessment methods discussed in the literature, only a few risk analysis techniques apply to the roof fall problem. For example, when determining the probability of occurrence two very different approaches are available: qualitative assessment and quantitative assessment. This paper will focus on a qualitative risk analysis technique.

For a roof fall event, the probability of occurrence term in equation 1 consists of two factors: the probability of a roof fall occurring and the potential for a miner being injured by this roof fall. Roof fall probability in this analysis is estimated with the RFRI while injury potential is estimated by the miner's exposure to hazardous roof conditions. Exposure to roof falls can range from constant (100%), when a miner is always present, to non-existent (0%), when a barrier prohibits a miner from entering the area. Roof fall probability and miner exposure can be determined for all areas of the mine accessible by the miner.

The consequence term in the risk equation typically refers to the severity of the event. When applied to a roof fall event, consequence is usually serious. For example, of the 7,738 miners injured from roof falls between 1996 and 2005, 1.3 percent resulted in a fatality, the rest were injuries requiring some medical attention. For most of the non-fatal injuries, the rock that struck the miner was probably relatively small. Since it is beyond our current abilities to forecast the size of a roof fall, any roof fall has the potential to result in a fatal injury. Therefore, the consequence should always be considered severe and given an assigned a value of 1. This effectively eliminates the consequence term from our analysis.

Therefore, a more appropriate definition for roof fall risk is:

$$\text{Roof Fall Risk} = (\text{Roof Fall Probability} \times \text{Miner Exposure to Roof Falls}) \times \text{Consequence} \quad (2)$$

A Qualitative Approach to Measure Risk Using the Roof Fall Risk Index

A qualitative risk analysis technique can be used to determine roof fall risk. A qualitative approach allows for estimations of roof fall probability and miner exposure. Roof fall probability can be qualified by calculating the RFRI over regions of an underground mine and by grouping RFRI values to appropriate roof fall probability categories (low, medium, and high). The other input for calculating roof fall risk, miner exposure, requires an estimation of miner activity through these same measured areas used in the RFRI analysis. These estimated parameters are used within a risk matrix (Table 4) to assign the relative roof fall risk for any accessible area within a mine. As roof conditions and patterns of miner activity change within a mine, roof fall risk changes accordingly.

RFRI values approaching 0 represent low defect conditions typically associated with stable roof conditions and imply a low roof fall probability. Conversely, RFRI values approaching 100 represent excessive defect conditions typically associated with unstable roof conditions, implying a high roof fall probability. Intermediate RFRI values fall into the medium roof fall probability category. Depending on the quality of the RFRI analysis, intermediate values could be defined with one or two categories yielding three or four columns or categories of roof fall probability (Table 4).

Table 4. A generalized risk matrix used in many qualitative risk analysis techniques.

Consequence	Probability of occurrence		
	Low value	•••	High value
Low value	Low risk		
•••		Medium risk	
High value			High risk

Miner exposure could be divided into three (low, medium, high) or four (never, rare, intermediate, continuous) categories, depending on the quality of the data gathered. Typical risk matrixes use 3 x 3 to 4 x 6 columns and rows, producing from 9 to 24 distinct risk rankings. The ultimate utility of these rankings lies in our ability to identify areas with the highest risk and to design controls that mitigate risk in a logical and thoughtful fashion.

Demonstration of a Roof Fall Risk Assessment Method

Let's examine how a roof fall risk assessment method might be applied. In a previous paper (Iannacchione, et al., 2006), the RFRI values at an active underground stone mine were calculated and placed on a mine map (Figure 2a, see Appendix B). The study area was divided into 226 measurement areas that ranged in size from that of a 15 x 15 m intersection to the 15 to 30 m long entries between intersections. The RFRI frequency distribution shows that most mine entries are stable (Figure 2b, see Appendix B). Entries with RFRI values below 30 were stable, while those with an RFRI greater than 40 were much less so. These break points produced reasonable groupings for defining three roof fall probability categories. Within the study area, measurement areas designated as having a low roof fall probability are assigned a value of 1, while medium probability areas have a value of 2, and high a value of 3 (Figure 2c, see Appendix B).

This analysis uses fictitious miner exposure data that replicated a main haulage route running north-south in the center of the section, a secondary haulage route running along the western portion of the section, active development faces along the southern perimeter of the section, entries behind the faces and between the haulage routes, and bermed-off areas to the east (Figure 3, see Appendix B). The main haulage route was busy with mine traffic and was assigned a continuous exposure with a value of 4. The secondary haulage route and the development face had intermittent miner activity with an exposure value of 3. The active section away from the haulage routes and the development area was rarely a site of miner activity, so it was given an exposure value of 2. The bermed-off areas were off-limits to miners and only occasionally inspected by the mine operator, and therefore assigned an exposure value of 1.

It is now possible to use a 3 x 4 risk matrix (Table 5) to estimate the risk associated with the 226 measurement areas within the study area. Twelve risk rankings are identified ranging from 1, the lowest, to 12, the highest. Within these twelve rankings, three risk levels are assigned. If the risk for roof falls is low, the risk values are between 1 and 3. In this example, if an entry was almost never visited by a miner, it would always represent a low risk condition, regardless of the roof conditions. Conversely, risk would be medium when roof fall probability was high and miner activity rare or high when miner activity was intermittent or continuous.

The relative roof fall risk was calculated for the 226 measurement areas and displayed on Figure 4 (see Appendix B). In this example, 69% of the measurement areas had a risk value between 1 and 3 and were designated as low risk for a roof fall injury. Nineteen percent had risk values between 4 and 6 and were designated a medium risk and 12% had risk values between 8 and 12 and were designated as high risk. Clearly a risk ranking method such as this allows the mine operator to focus attention on high risk areas in the main haulage and development entries where proactive tactical and strategic controls to mitigate these hazardous conditions can be applied.

Table 5. Qualitative risk analysis using a risk matrix, where values between 1 and 3 are low (acceptable) risk, values between 4 and 6 are medium (undesirable or acceptable with management review and approval) risk, and values between 8 and 12 are high (unacceptable) risk. The exposure period used for this example could range from one to six months.

Exposure	Roof fall probability		
	Low = 1 (RFRI <30)	Medium = 2 (RFRI 30 to 40)	High = 3 (RFRI >40)
Never =1	1	2	3
Rare = 2	2	4	6
Intermittent = 3	3	6	9
Continuous = 4	4	8	12

Summary and Conclusions

In practice, unstable roof and the risks it presents within the underground workplace are often only partially known. Because risk assessment and risk management methods rely on hazard recognition practices and controls that either reduces the risk of the hazard or lowers worker exposure, they have the potential to increase roof fall hazard recognition efforts and make it possible to address the highest risk roof fall hazard. When risks are ranked, mine operators have the opportunity to: 1) investigate strategic or tactical controls, 2) monitor the performance of the controls, and 3) modify them as needed, in an iterative process, thus continually addressing the highest roof fall risk areas.

There are four basic steps to the roof fall risk assessment method used in this paper:

1. <u>Recognize and rate defective roof conditions that represent roof fall hazards.</u> This is accomplished with the RFRI hazard assessment technique.
2. <u>Determine the roof fall probability for specific roof conditions.</u> This is accomplished using qualitative analysis techniques where RFRI values were grouped into logical probability categories.
3. <u>Evaluate the exposure of miners to roof falls in the study area.</u>
4. <u>Rank the roof fall risk for all active workplaces within the mine using a risk matrix.</u> Rating or ranking roof fall risks helps to identify what areas should be monitored most closely by the mine operators and miners alike. It is also critical for prioritizing the areas where administrative and/or engineering controls are needed most to reduce these risks.

This paper demonstrates how roof fall risk can be assessed by appropriately designed hazard assessment and qualitative risk analysis techniques. These techniques help to rate hazards, rank roof fall risk over a mine property, provide a means to communicate information with all levels of the mining operation, track changing conditions as the mine develops, train less-experienced miners to recognize hazardous conditions, and develop controls/plans that are the hallmark of a proactive approach to mitigate risk to miners.

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Appendix A

Table 1. Roof fall injury and fatality rates over the 10-year period from 1996 to 2005 for underground mines.

Year	Coal		Metal		Nonmetal		Stone		Total	
	Injury rate	Fatal rate	Injury rate	Fatal rate	Injury rate	Fatal rate	Injury rate	Fatal rate	Injury rate	Fatal rate
1996	1.8	0.029	2.08	0.016	0.36	0.0	0.58	0.116	1.71	0.028
1997	1.9	0.02	2.12	0.032	0.43	0.0	0.5	0.055	1.8	0.022
1998	2.03	0.033	2.07	0.052	0.44	0.0	0.52	0.0	1.89	0.032
1999	1.89	0.031	1.82	0.061	0.59	0.0	0.92	0.051	1.77	0.033
2000	1.98	0.011	1.63	0.023	0.4	0.0	0.45	0.0	1.79	0.011
2001	1.79	0.03	1.01	0.09	0.31	0.0	0.52	0.0	1.58	0.032
2002	1.75	0.011	0.94	0.0	0.31	0.0	0.59	0.0	1.55	0.009
2003	1.51	0.009	0.86	0.0	0.3	0.0	0.43	0.0	1.34	0.007
2004	1.5	0.008	0.68	0.0	0.25	0.0	0.31	0.0	1.31	0.007
2005	1.34	0.023	0.81	0.0	0.33	0.0	0.24	0.0	1.19	0.019
Total	1.75	0.021	1.51	0.03	0.38	0.0	0.5	0.021	1.6	0.021

Injury rate = Roof fall injuries (Degree of Incident, class 1-6) per 200,000 hours worked underground
Fatal rate = Roof fall fatalities per 100,000 miners

Appendix B

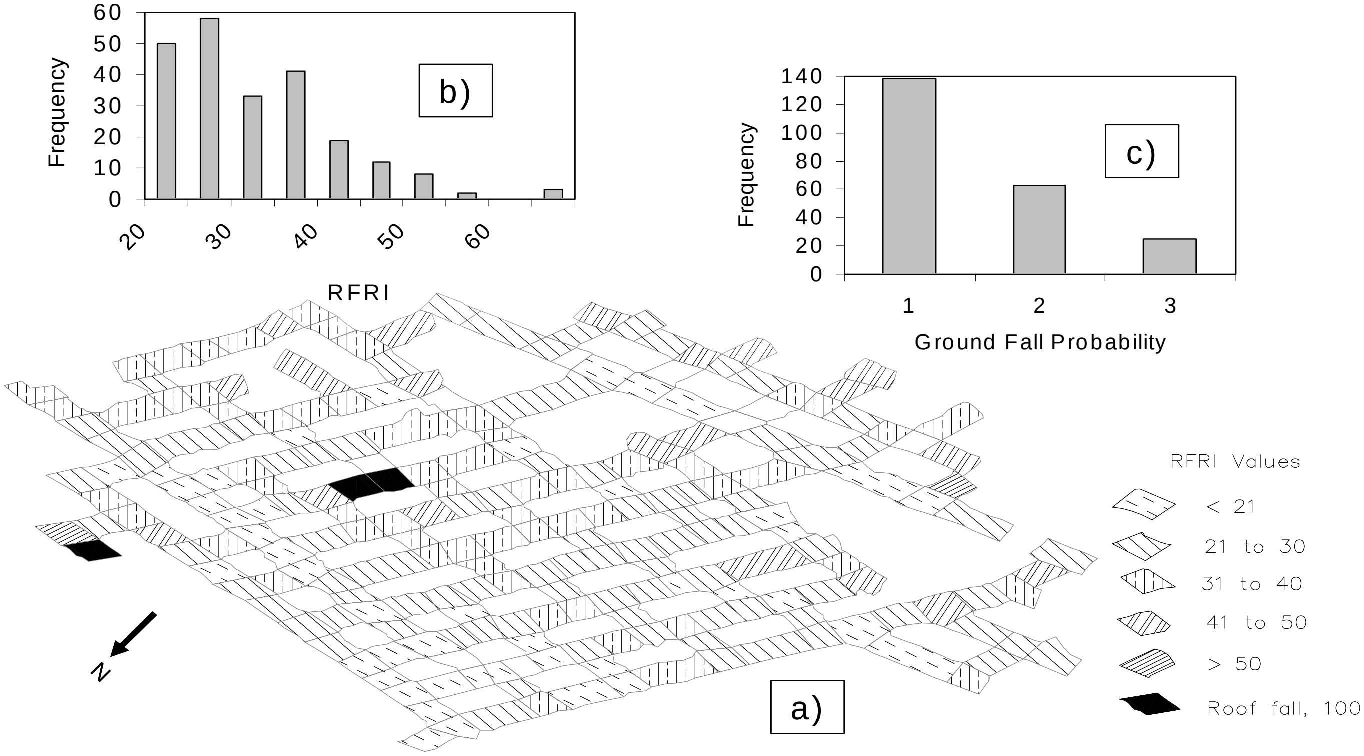

Figure 2. a) RFRI values for the 226 measurement areas that comprised the study area, b) histogram of RFRI frequency, and c) histogram of Roof Fall Probability categories where low =1, medium = 2, and high = 3.

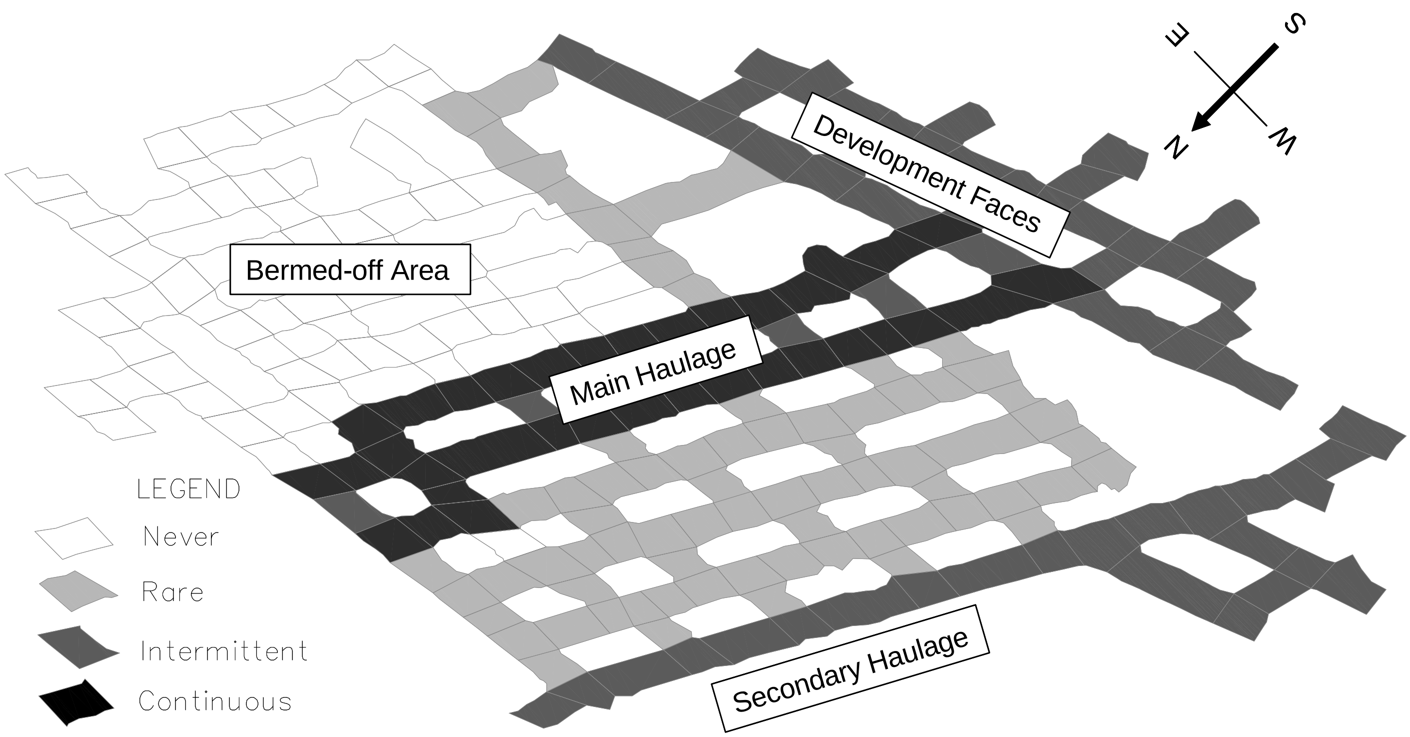

Figure 3. Miner activity and related miner exposure for the 226 measurement areas.

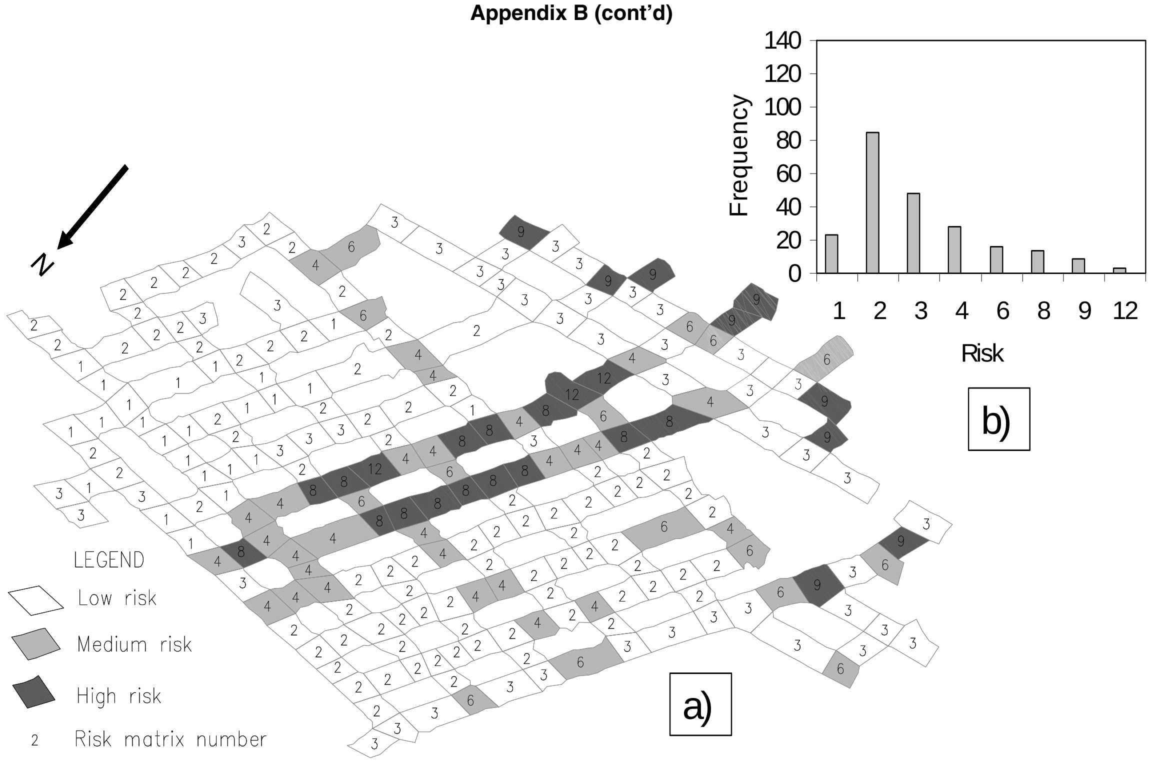

Figure 4. (a) Ranked risk for roof falls over the 226 measurement areas, and (b) histogram of roof fall risk values throughout the study area.